Fermi National Accelerator Laboratory

FERMILAB-Conf-89/255-A
December 1989

NAGW-1340
IN-90-CR
252685
28P

COSMOLOGY AND THE WEAK INTERACTION

David N. Schramm

University of Chicago
5640 S. Ellis Avenue
Chicago, IL 60637
and
NASA/Fermi Astrophysics Center
Fermi National Accelerator Laboratory
Box 500
Batavia, IL 60510-0500

ABSTRACT

The weak interaction plays a critical role in modern Big Bang cosmology. This review will emphasize two of its most publicized cosmological connections: (1) Big Bang nucleosynthesis and (2) Dark Matter. The first of these is connected to the cosmological prediction of of Neutrino Flavours, $N_\nu \sim 3$ which is now being confirmed at SLC and LEP. The second is interrelated to the whole problem of galaxy and structure formation in the universe. This review will demonstate the role of the weak interaction both for dark matter candidates and for the problem of generating seeds to form structure.

Proceedings of the Wein 89 International Symposium on Weak and Electromagnetic Interactions in Nuclei, Montreal, May, 1989

(NASA-CR-186170) COSMOLOGY AND THE WEAK INTERACTION (Chicago Univ.) 28 p CSCL 03B

N90-14169

Unclas
G3/90 0252685

INTRODUCTION

Some of the most critical problems in cosmology today involve the weak interaction, in particular, Big Bang Nucleosynthesis and dark matter. The weak interaction is fundamental to all Big Bang Nucleosynthesis results such as neutrino counting and the limit on cosmological baryon density. This latter limit is the crux of the argument leading to non-baryonic dark matter. The leading dark matter candidates are weakly interacting and some of the proposed seed mechanisms for forming structure also involve the weak interaction. It is the arena of dark matter and galaxy formation where traditional astronominal observations of cosmological relevence come face to face with elementary particle models, both for predicting new and exotic types of matter and for predicting the origin of various types of seeds that eventually produce the structure.

This overview will go through the Big Bang Nucleosynthesis arguments as to why there must be dark matter in the universe and then discuss the types of dark matter and the proposed structure formation mechanisms, and finally discuss observations and experiments that will eventually determine the answers to the problem. Remember that the key reason why the cosmology/particle interface is so vital today is the close interplay between theory, observation and experiment. Unlike cosmology of past centuries or even past decades, current models and ideas are indeed testable and those observations and experiments are being carried out.

THE NEED FOR DARK MATTER

The arguments requiring some sort of dark matter fall into two separate and quite distinct areas. One is the argument using Newtonian mechanics applied to various astronomical systems that show that there is more matter present than the amount that is shining. These arguments are summarized in the first part of Table 1. It should be noted that these arguments reliably demonstrate that galaxies have dark halos that carry at least 90% of the total mass of the galaxy. In other words, the halos seem to have a mass ~ 10 times the visible mass. The arguments do not in any way imply that Ω is unity from dynamical considerations alone.

The other argument is what we choose to call the inflation paradigm. This is the argument that the only long-lived natural value for Ω is unity, and that inflation or something like it provided the early universe with the mechanism to achieve that value and thereby solve the flatness and smoothness problems. It should be remembered that it is this latter argument, when confronted with the results of Big Bang Nucleosynthesis (see Fig. 1 as well as Table 1), that tells us that Ω in baryons Ω_B is ~ 0.01 and therefore that if Ω total is truly unity, then the bulk of the mass of the universe must be in the form of

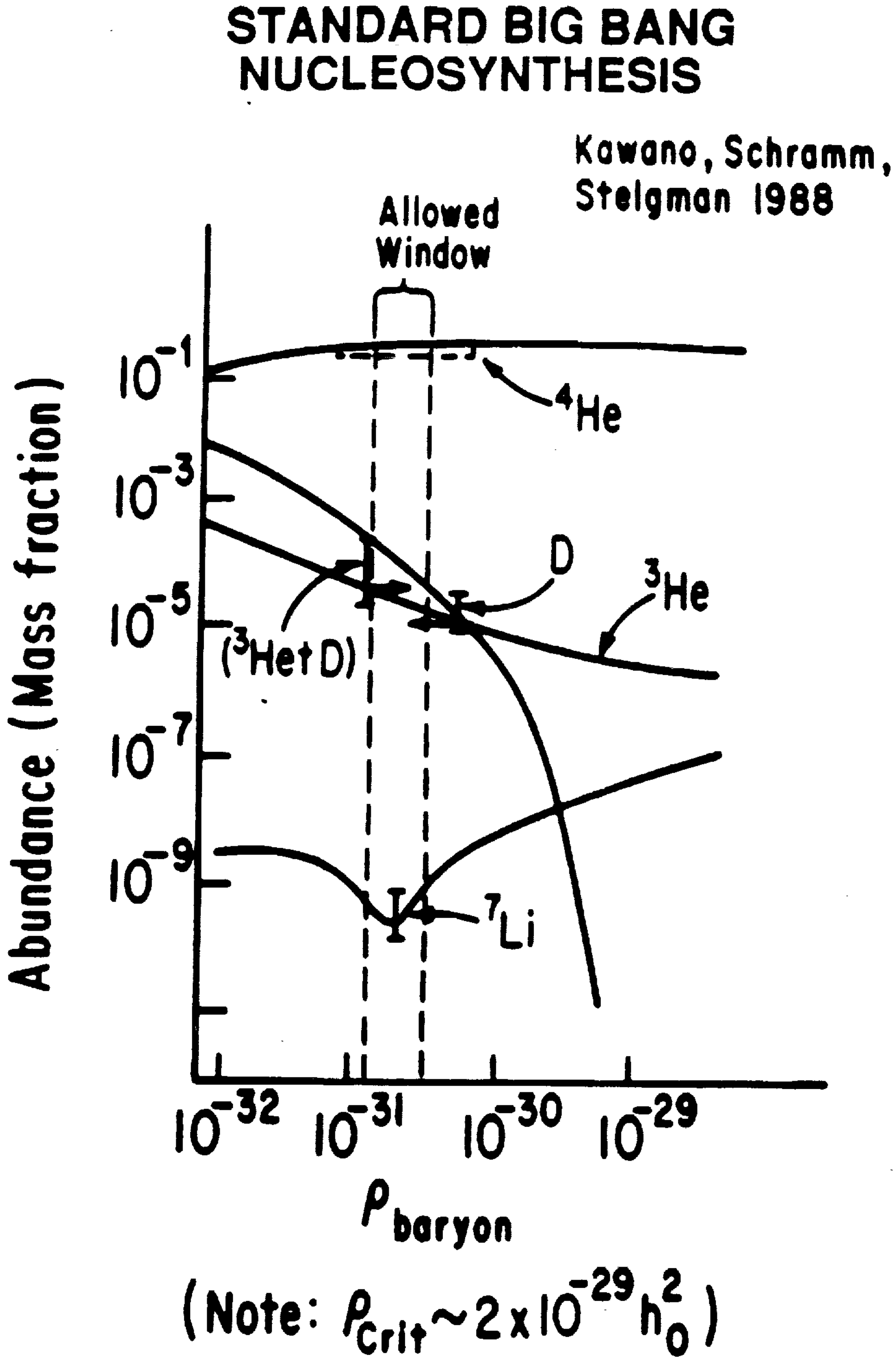

Figure 1. Big Bang Nucleosynthesis abundance yields versus baryon density for a homogeneous universe.

TABLE I

"OBSERVED" DENSITIES

$$\left[\Omega \equiv \rho/\rho_c \text{ where } \rho_c = 2 \cdot 10^{-29} h_0^2 g/cm^3 \text{and } h_o \equiv \frac{Ho}{100 \text{ km/sec/mpc}}\right]$$

Neutonian Mechanics

(cf. Faber and Gallagher 1979)

$\Omega_{\text{visible}} \sim 0.007$ ($\sim$ *factor of* 2)

Ω_{binaries} ~ 0.07 ($\sim$ factor of 2)
small groups
extended flat relation curves

$\Omega_{\text{clusters}} \sim 0.1$ *to* 0.3

Big Bang Nucleosynthesis (with $t_u \gtrsim 10^{10}$yrs.)

(c.f. Kawano, Schramm and Steigman 1988 and ref. therein)

$0.03 \leq \Omega \leq 0.12$

Preliminary Large Scale Studies

IRAS red shift study (Strauss, Davis, Yahil 1989) $\Omega \gtrsim 0.3$

Density redshift counts (Loh and Spillar 1988) $\Omega \sim 1 \pm 0.6$

Inflation Paradigm

(Guth 1980, Turner 1986)

$\Omega = 1$

some sort of non-baryonic matter. Thus, our need for exotica is dependent on inflation and Big Bang Nucleosynthesis and not on the existence of dark galactic halos. This point is frequently forgotten, not only by some members of the popular press but occasionally by active workers in the field. Therefore, rather than spending any further time on the dynamical arguments, I will focus my attention on a brief review of the argument for the inflation paradigm and then concentrate on Big Bang Nucleosynthesis, since it is really the pivotal argument that drives us to non-baryonic and, therefore, exotic solutions. We will see that Big Bang Nucleosynthesis really depends crucially on the weak intereaction.

We will also focus on the point that Big Bang Nucleosynthesis not only requires non-baryonic matter, but it also requires the bulk of the baryons in the universe to be dark. In fact, locating the dark baryons may be a very important way of discerning the nature of the non-baryonic component as we shall see. Recently, some clever possible loop holes in the Big Bang Nucleosynthesis argument have been proposed. These shall be discussed and shown probably not to be as critical as they initially seemed.

THE INFLATION PARADIGM

The flatness problem is a well known cosmological problem for any classic Big Bang cosmology. It basically notes that the density parameter of Ω evolves with time. If Ω is > 1, Ω will eventually go toward infinity; if Ω is < 1, it will eventually go to 0. Only if Ω is exactly equal to 1, does it remain at that value indefinitely. The time scale on which Ω changes is the gravitational time scale which is approximately the age of the universe. Thus, at the present time, Ω is changing on a time scale of tens of billions of years if Ω is significantly different than unity today. However, back at the time of Big Bang Nucleosynthesis, Ω was changing on a time scale of seconds. If we extrapolate as far as any rational person has confidence, back to the Planck time, then Ω was changing on time scales of $\sim 10^{-43}$ per second. Therefore, in order for us still to be here today and talk about it, Ω had to be fine tuned to be equal to unity to nearly 60 decimal places at the Planck time. Another way of saying this is that since our existence is not compatible with Ω of 0 or infinity, the only long term value that Ω can have is unity. Hence, baring the possibility of our living at an epoch in cosmic time when Ω has just dropped below unity for the first time, but is still far from 0, we would otherwise say that Ω is unity.

These arguments went on long before *inflation* provided us the natural physical mechanism to drive Ω to unity in the first moments of the universe. Thus, it did not have to rely on some arbitrary fine-tuned initial condition. Inflation[1] is the rapid expansion of the early universe that would take a wide range of initial conditions and convert them to conditions where Ω was unity to a high accuracy. Although the detailed physical mechanism for driving the expansion is not well determined and differs in different grand unified theories, a basic point is that any scalar field present in the early universe will cause inflation.[2] Inflation provides us with a plausable mechanism to set the initial conditions and avoid special fine tuning. This drives most cosmologists to believe Ω must be unity today.

BIG BANG NUCLEOSYNTHESIS

Figure 1 shows the abundances verses baryon density for standard homogeneous Big Bang Nucleosynthesis. The actual Big Bang calculations themselves are natural evolution from the early primitive work of Alpher, Bethe and Gamow[3] evolving through the almost complete picture used by Alpher, Follin and Herman[4] and receiving only minor physical modifications since the first post $3K$ discovery calculations with numerical reaction networks of Peebles,[5] Wagoner, Fowler and Hoyle.[6] However, it should be remembered at the time of Wagoner, Fowler and Hoyle, that the only nucleus produced in the Big Bang that was thought to be of significance was ^4He. Fowler, Greenstein and Hoyle[7] had argued that the other light elements were made in protostellar processes. Thus, during the 1960's the abundances of deuterium, ^3He, and ^7Li produced in the Big Bang were merely a curiosity, and were not seriously utilized for cosmological purposes. That situation changed dramatically in the 70's, when a variety of events occurred affecting Big Bang Nucleosynthesis.

The first point of significance was a demonstration, not only that the Fowler, Greenstein and Hoyle process failed,[8,9] but the eventual dramatic statement that deuterium cannot be produced in significant quanities in any astrophysical location other than in the big bang due to its basic nuclear fragility.[10] The development of these nuclear arguments, coupled with the development of the observations, in particular the Copernicus satellite finding deuterium in the interstellar medium[12] and the implications for deuterium from solar wind observations[13] on the moon and meteoritic observations,[14] cemented deuterium's use as a powerful density constraint. This helped support, for example, the arguments of Gott, Gunn, Schramm and Tinsley.[11]

Once deuterium was established as cosmological, similar but more complex procedures were applied to establishing the cosmological relevance of ^3He and ^7Li as demonstrated by Yang, Rood, Steigman and Schramm[15] following the important ^3He work of Tinsley, Rood and Steigman.[16] In particular, it was eventually shown that ^3He plus the ^2H that is converted to of ^3He in stars provides a strong lower bound on density, since ^3He is also manufactured in stars.[17] Furthermore, it was noted in the series of papers by the Chicago Group and their collaborators[15,17,18] that the only allowed value for Li consistent with the ^3He and deuterium observations will be a value of Li near the minimum of its abundance curve, namely, Li/H of approximately 10^{-10}. At the time this was first noted, it seemed somewhat problematic because Li in Pop I objects and in the interstellar medium seemed to imply a value an order of magnitude higher. However, agruments were made that the Pop I abundance might have been significantly enhanced by later production processes. The definitive observation came in 1980 when the Spites[19] measured the Li in the extreme Pop II stars and found the higher surface temperature Pop II stars all had the same Li abundance, and it was at the level of 10^{-10} in agreement with the minimum derived from the Big Bang Nucleosynthesis agruments.

With ^7Li as a keystone, standard Big Bang Nucleosynthesis was fitting abundances all the way from ^4He at 25% by mass down to ^7Li at 10^{-10} by number; a range of over 9 orders of magnitude. Such quantitative agreement not only seconded the 3K background's establishment of the basic Big Bang model, but also led to the establishment of the particle/cosmology connection. It said that we understood the universe not just at the epoch of the background decoupling ($t \sim 10^5 yrs.$), but also at the epoch of Big Bang Nucleosynthesis ($t \sim 1 sec.$).

Big Bang Nucleosynthesis was used to predict[20] the number of fundamental particle types, which explicitly substantiated the particle/astro connection by making a cosmological prediction about a quanitity of explicit interest to particle physicists and by enabling experimental tests in accelerator laboratories to be made regarding the Big Bang model.[21,22]

In the mid-1970's, when particle accelerators were finding more and more fundamental particles, cosmologists[20] argued that the number of families cannot continue to increase or there would be a conflict between the observed Helium abundance and the Helium produced in the Big Bang. The most recent re-evaluation of the cosmological limit using current neutron lifetime measurements of $\tau_n = 890 \pm 4$ from Mampe et al.[82] are shown in Figure 2. If the current best [83] primordial ^4He abundances are used ($Yp \sim 0.232 \pm 0.004$), then even four families appear to be excluded with three working fine. The new SLC results[84] seem to experimentally support these cosmological results. Thus, particle accelerators are now verifying cosmological predictions.

For dark matter, the important implication of nucleosynthesis was that Ω_B was constrained to be between 0.03 and 0.12. Thus, the universe cannot be closed with baryons, but furthermore the lower bound was greater than Ω visible. To obtain this lower bound it should be noted that one has added the additional constraints[23] that the age of the universe is greater than 10^{10} years, which thus constrains any $\Omega_{total} = 1$ model to have an H_0 of less than $70 km/sec/Mpc$. It was noted by Gott et al.,[11] that the Big Bang Nucleosynthesis derived Ω_B is in good agreement with the $\Omega's$ implied by the dynamics of galactic systems. Thus, to explain halos, one is not forced to look beyond some form of baryonic dark matter. It is only if one goes to an Ω of unity, or, to be more specific, Ω

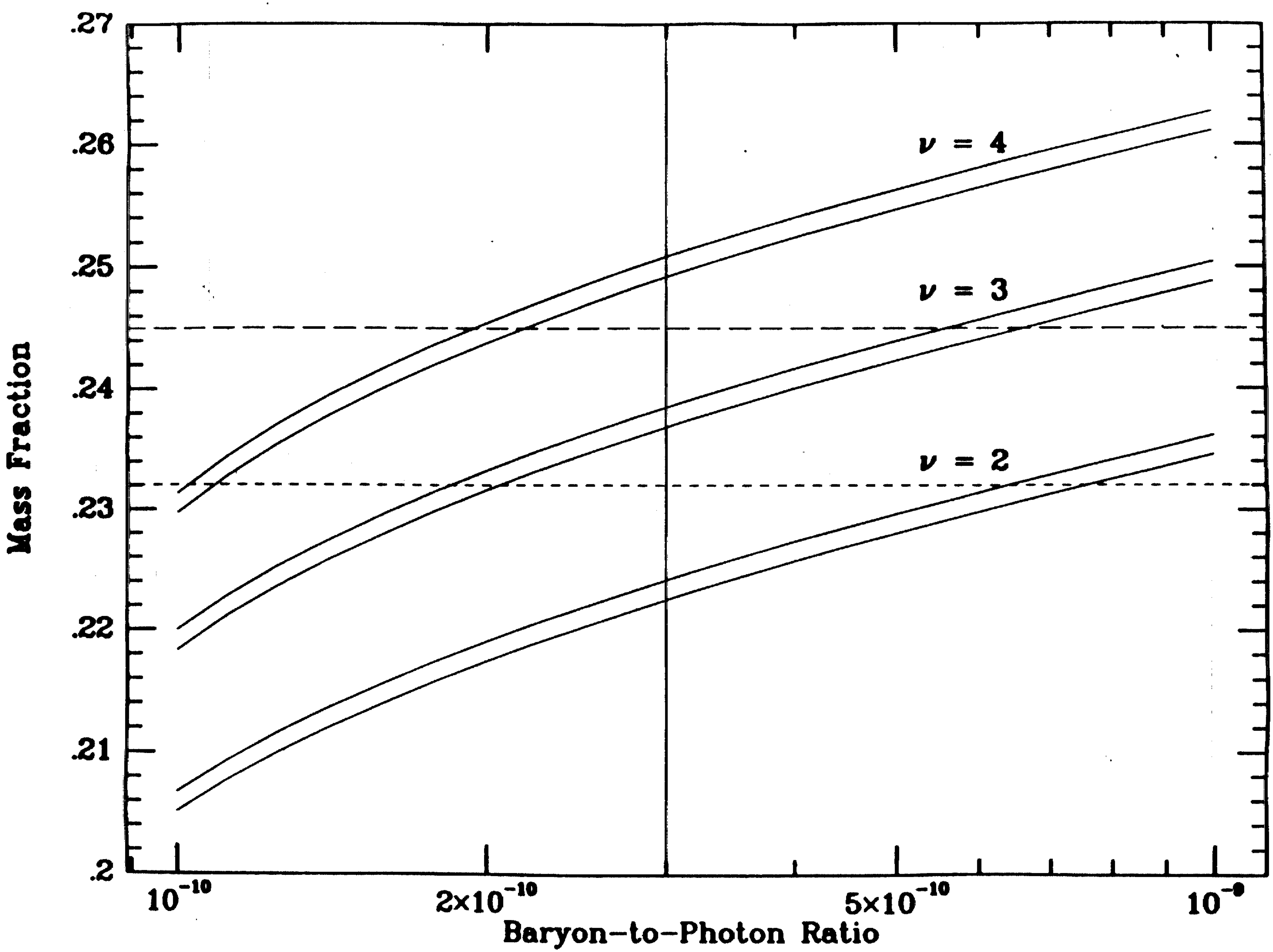

Figure 2. Helium mass fraction versus the cosmological baryon-to-photon ratio. The vertical line is the lower bound on this ratio from considerations of ^2D and ^3He (see Yang et al.) (Using ^7Li as a constraint would move the vertical line only slightly to the left.) The lower horizontal line is the current best fit zero metalicity extrapolation of 0.232. The 3σ upper bound of 0.245 is also shown. The width of the lines for $N_\nu = 2,3$ and 4 is due to $\tau_n = 890 \pm 4_s$. Note that $N_\nu = 4$ appears to be excluded barring a systematic error upward in Y_p which would be contrary to current sys-

≥ 0.12 for the standard homogeneous model, that one is really forced to exotic matter.[24]

Before discussing such matter let us look at two possible loopholes in the argument. These loopholes are: (1) fluctuations generated at the quark-hadron transition and (2) alterations of nucleosynthesis by late decaying massive particles.

This latter model was developed most fully by Dimopoulos et al.[33] In it they noted that if some massive unstable particle exsisted, and decayed shortly after the time of normal nucleosynthesis, it would regenerate nucleosynthetic results that were quite different from the standard model and could even fit the observed abundances with somewhat different values of baryonic density and/or numbers of neutrinos. A key point about these calculations, though, was that they predicted that the bulk of the lithium coming from the Big Bang will be ^6Li rather then ^7Li. Following the arguments of Brown and Schramm,[34] the Li isotopic ratio has been examined in extreme Pop II stars by Hobbs, Pilachowski and De Young.[85] They found no evidence for any ^6Li in these stars. Thus, unless even these stars destroyed their ^6Li, it appears unlikely that the decaying scenario is valid.

As to the quark-hadron transition possibilities, much has been written. It was first noted by Applegate, Hogan and Sherrer,[35] followed by work by Alcock, Fuller and Mathews,[36] that if a quark-hadron transition were a first order phase transition, then density fluctuations produced at the phase transition could yield inhomogeneities at the time of nucleosynthesis. Furthermore, the differential diffusion of neutrons relative to protons out of the density inhomogeneities will yield a variable neutron/proton ratio, as well as the previously studied density fluctuations. (For previous studies of inhomogeneities, see Yang et al.[17]) In the initial calculations, it was thought that one might be able to obtain an Ω_B of unity while fitting all of the light abundances with the exception of Li, which would have been over-produced by a significant amount. Later work by Fowler and Malaney[37] argued that when a more detailed treatment of the two-phase model was carried out that included back defusion of the neutrons, then the Li could be depleted to more acceptable values. However, work by Kurki-Suonio, and Matzner[39] and Alcock et al.[40] showed that back defusion also resulted in high helium abundances. Whether parameters could be found that enabled this He to be depleted is problematic among the different groups. (Density contrasts $\gtrsim 10^4$ may give lower He, but are they realistic? Can variations in the detailed treatment of the phase boundary help, etc.?) However, they all seem to be in agreement that, except for some very narrow range in parameter space, Li and He are usually over-produced for high Ω_B. In phase transitions, one usually expects some distribution of parameters, not single values. That a phase transition would exactly pick out those parameters that avoid excessive over-production of Li and He seems difficult, especially when one realizes that the separation of the nucleation sites required is the order of hundreds of meters for a phase transition that operates on Fermi scale processes. However, until this is completely explored, there clearly remains a loophole that must be investigated further.

Ignoring this possible loophole (which now appears far less compelling than it did in the initial papers), let us apply to the quark-hadron transition the normal abundance constraints that we have used from nucleosynthesis and not relax the Li constraint. If we apply our normal constraints we obtain[41] Figure 3. The parameter on the vertical scale there is the separation of the nucleation sites measured in meters at the time critical for the phase transition. The horizontal parameter is again the density in baryons. Once the Pop II constraints on Li are put in, the highest baryonic density to be achieved is only slightly higher than the standard models, regardless of separation of nucleation sites. Similarly, the lower bound does not drop significantly. It should also be noted that these kinds of arguments can be turned around to constrain the parameters of the phase transition, since values of over one hundred meters appear to be excluded by nucleosynthesis. This same kind of argument was also made by Reeves and Audouze[42] and Tarasawa and Sato.[38]

Before leaving Big Bang Nucleosynthesis, it should be remembered that the quark-hadron loophole is critically dependent on Li. One point that has been raised is that if we are willing to use the Li for this argument, we should understand fully how Li evolves in the galaxy. A key question for Li has been how to get from the Pop II abundance of $Li/H \sim 10^{-10}$ to the Pop I abundance of $Li/H \sim 10^{-9}$. Some[40] have argued that perhaps Li is depleted from some high initial value down to both Pop I and Pop II values. However, recently Dearborn, Schramm, Steigman and Truran[43] have found that Li will be produced in type II supernovae and thus will be enhanced in exactly the same objects that produce the metal abundance of the Galactic disk. With this mechanism it is easy to understand why the Pop I value is an order magnitude higher than the Pop II value and why it appears constant for old as well as young Pop I stars that have not depleted their surface Li. In fact, if Li can be proven to be made in supernovae, then it will be impossible to reconcile successive high Li production and $\Omega_B = 1$ universes with the galactic evolution of Li. Thus, Li evolution continues to be a critical point of study.

DARK MATTER CANDIDATES

Table 2 summarizes both the baryonic and non-baryonic dark matter candidates. Some baryonic dark matter must exist since we know that the lower bound from Big Bang Nucleosynthesis is greater than the upper limits on the amount of visible matter in the universe. However, we do not know what form this baryonic dark matter is in. It could either be in condensed objects in the halo, such as brown dwarfs and jupiters (objects with $\lesssim 0.08$ solar masses so they are not bright shining stars), or black holes (which at the time

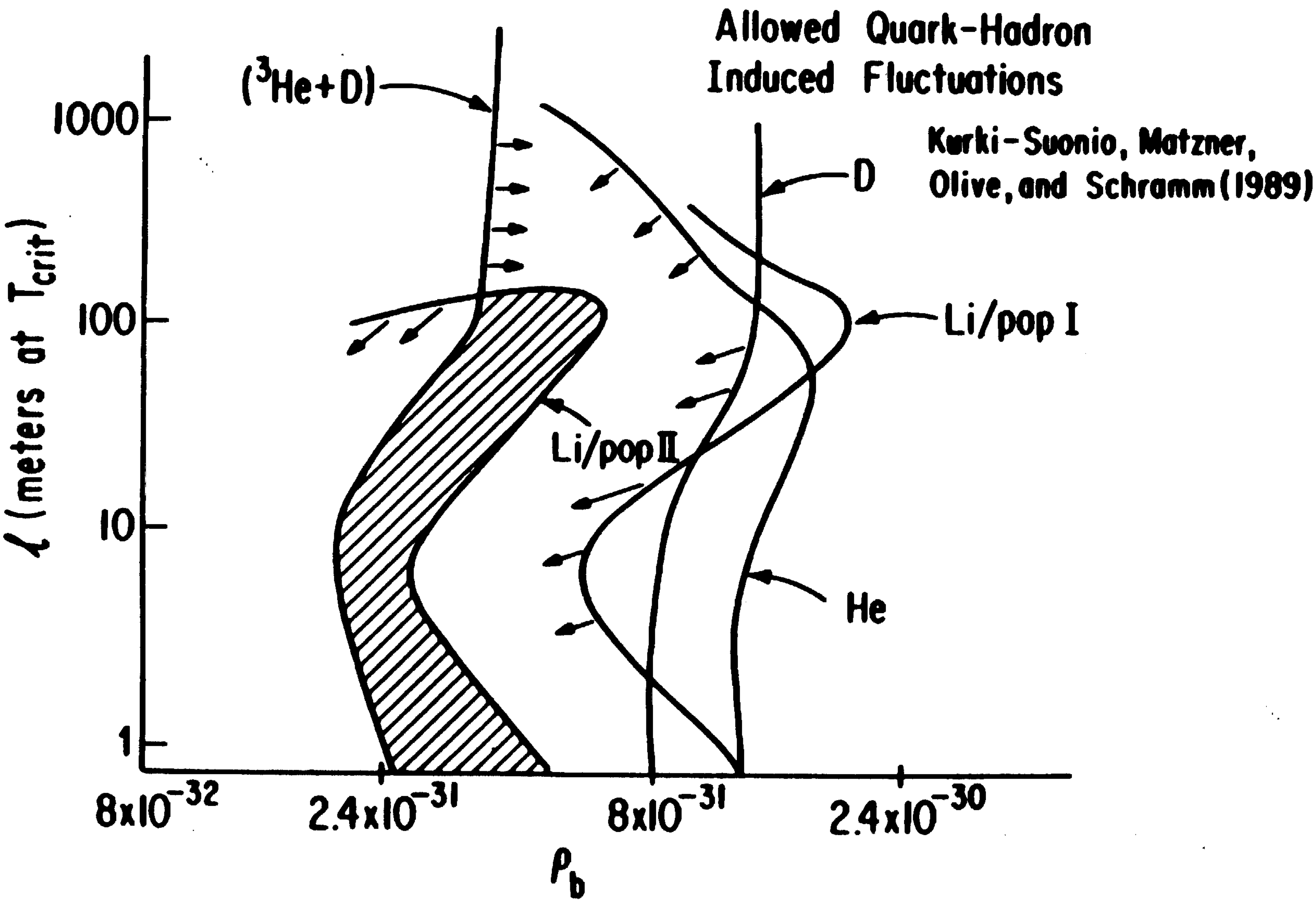

Figure 3

Allowed parameter space for quark-hadron induced fluctuations with nucleation sites separated by distance ℓ and average baryon.

TABLE II

"DARK MATTER CANDIDATES"

Baryonic (BDM)	
Brown Dwarfs and/or Jupiters	$M \lesssim 0.08 M_{\odot}$
Blackholes	$M \gtrsim 1 M_{\odot}$
Hot intergalactic gas	$M \sim 1GeV,\ T \sim 10^6 K$
Failed galaxies	$M \gtrsim 10^5 M_{\odot}$
Non Baryonic	
Hot (HDM)	
Low Mass Neutrinos	$M_{\nu} \sim 20 \pm 10 eV$
Cold (CDM)	
Massive Neutrinos	$M_{\nu} \sim 3GeV$
Wimps, Lightest Supersymmetric Particle (Photino, Gravitino, Sneutrino)	$M_{susy} \sim 4GeV$
Axions	$M_a \sim 10^{-5} eV$
Planetary mass black holes	$M \sim 10^{15} g - 10^{-30} g$
Quark nuggets	$M \sim 10^{15} g$
Topological debris (monopoles higher dimensional knots, balls of wall, etc.)	$M \gtrsim 10^{16} GeV$

of nucleosynthesis would have been baryons). Or, if the baryonic dark matter is not in the halo, it could be in hot intergalactic gas, hot enough not to show absorption lines in the Gunn-Peterson test, but not so hot as to be seen in the x-rays. Evidence for some hot gas is found in clusters of galaxies. However, the amount of gas in clusters is probably not enough to make up the entire missing baryonic matter. Helfand[44] has argued that the isotropic x-ray background may be due to hot intergalactic gas in sufficent density to account for all the dark baryons. If verified, this would reduce the possibilities of halos containing condensed dark baryons, since all the baryonic matter would be accounted for. Another possible hiding place for the dark baryons would be failed galaxies, large clumps of baryons that condense gravitationally, but did not produce stars. Such clumps are predicted in galaxy formation scenarios that include large amounts of biasing where only some fraction of the clumps shine.

Hegyi and Olive[45] have argued that dark baryonic halos are unlikely. However, they do allow for the loopholes mentioned above of low mass objects or of massive black holes. It is worth noting that these loopholes are not that unlikely. If we look at the initial mass function for stars forming with Pop I composition, we know that the mass function falls off roughly like a power law for standard size stars, as was shown by Salpeter. Or, even if we apply the Miller-Scalo mass function, the fall off is only a little steeper. In both cases there is also some sort of lower cut-off near $0.1M_{\odot}$. However, we do not know the origin of this mass function and its shape. No star formation model based on fundamental physics predicts it. We do believe that whatever the origin of this mass function is, that it is probably related to the metalicity, since metalicity affects cooling rates, etc. It is not unreasonable to expect that the initial mass function that was present in the primordial material (which had no heavy elements but only the products of Big Bang Nucleosynthesis) would be peaked either much higher than the present mass funtion or much lower; higher if the lower cooling from low metals resulted in larger clumps, or lower if some sort of rapid cooling processes ("cooling flows") were set up during the initial star formation epoch, as seems to be the case in some primative galaxies. In either case, moving either higher or lower produces the bulk of the stellar population in either brown dwarfs and jupiters or into massive black holes. Thus, the most likely scenario is that a first generation of condensed objects would be in a form of dark baryonic matter that could make up the halos and could explain why there is this interesting coincidence between the implied mass in halos and the implied amount of baryonic material. However, it should also be remembered that to follow through with this scenario, one would have to have the condensation of the objects occur prior to the formation of the disk. Recent observational evidence[46] seems to show disk formation is relatively late, occurring at red shifts $Z \lesssim 1$. Thus, the first several billion years of a galaxy's life may have been spent prior to the formation of the disk. In fact, if the first large objects to form are less than galactic mass, as many scenarios imply (c.f. York et al.[86]), then mergers are necessary for eventual galaxy size objects. Mergers stimulate star formation while putting early objects into halos rather than disks. Thus, while making halos out of exotic material may be more exciting, it is certainly not impossible for the halos to be in the form of dark baryons. One application of William of Occum's famous razor would be to have us not invoke exotic matter until we are forced to do so.

Non-baryonic matter can be divided following Bond and Szalay[47] into two major categories for cosmological purposes: hot dark matter (HDM) and cold dark matter (CDM). Hot dark matter is matter that is relativistic until just before the epoch of galaxy formation, the best example being low mass neutrinos with $m_\nu \sim 20eV$. (Remember $\Omega_\nu \sim \sum \frac{m_\nu(eV)}{100\ h^2}$.)

Cold dark matter is matter that is moving slowly at the epoch of galaxy formation. Because it is moving slowly, it can clump on very small scales, whereas HDM tends to have more difficulty in being confined on small scales. Examples of CDM could be massive neutrino-like particles with masses greater than several GeV or the lightest supersymmetric particle which is presumed to be stable and might also have masses of several GeV. Axions, which, while very light, would also be moving very slowly[48] and thus would clump on small scales. Or, one could also go to non-elementary particle candidates, such as planetary mass blackholes[49] or quark nuggets of strange quark matter, also found at the quark-hadron transition. Another possibility would be any sort of massive topological remnant left over from some early phase transition.

When thinking about dark matter candidates, one should remember the basic work of Zeldovich,[50] later duplicated by Lee and Weinberg,[51] which showed for a weakly interacting particle that one can obtain closure densities, either if the particle is very light, $\sim 20eV$, or if the particle is very massive, $\sim 3GeV$. That is because, if the particle is much lighter than the decoupling temperature, then its number density is the number density of photons (to within spin factors and small corrections), and so the mass density is in direct proportion to the particle mass since the number density is fixed. However, if the mass of the particle is much greater than the decoupling temperature, then annihilations will deplete the particle number. Thus, as the temperature of the expanding universe drops below the rest mass of the particle, the number density is depleted via annihilations. For normal weakly interacting particles, decoupling occurs at a temperature of $\sim 1MeV$, so higher mass particles are depleated.

Before leaving the discussion of DM candidates, it might be noted that in addition to the curious coincidence of the density of baryons being approximately equal to the density implied by halos, there is another coincidence which may have exactly the opposite resolution. This is the coincidence in the ratio of halos to visible matter (~ 10), which is the same as the ratio of critical density to the baryonic density (also about 10). This coincidence is nicely explained in CDM models with biasing, since in these models there will be many clumps of baryons and CDM, but only some biased fraction would shine. Once the ratio of CDM to baryons is set in the early universe, it would propagate in all objects and thus would yield the same ratio of shining to non-shining matter everywhere. Of course these "coincidences" are only good to factors of a few, so as observational data improves, the "coincidences" may vanish.

GALAXY FORMATION MODELS

As much a part of any DM scenario as the DM itself are the seeds that enable the DM and the baryons to form the observed clusters of galaxies and other structures. While many statements are frequently made about the ability of one or another kind of DM to make realistic structures, those statements are always made in the context of an explicit model of galaxy formation. Since we do not really know how galaxies form, all such statements need to be taken with several grains of salt. At the present time there are two basic galaxy formation scenarios. One uses quantum induced Gaussian fluctuations generated at the end of inflation. The other uses some topological remnant, again produced by some new fundamental physics. It should be noted that each of these mechanisms involves new fundamental physics, and it should also be noted that prior to the marriage of cosmology with particle physics we had no models for generating the initial seeds, and fluctuations were merely put in by hand. Now we have models that do relate the structure formation seeds to fundamental physics, but the fundamental physics we need is not just the standard model particle physics interactions.

The quantum induced Gaussian fluctuation model with the production of the Harrison-Zeldovich spectrum has been the standard model for galaxy formation in the '80's. And with that model, CDM is favored, since HDM is not able to make small galaxy-like structures fast enough. However, CDM with Gaussian fluctuations, as we will see, may run into problems on the large scale side if present reported observations continue to hold up. The advantages of the CDM plus Gaussian model are that it is easy to calculate; it has been explored in far more detail than any of the other models; and it does amazingly well considerating the rate at which new observations are being generated. The most detailed work on these models have been the numerical simulations of Frenk, White, Davis and Efstathiou.[52]

The alternative of using topological remnants as the seeds, as opposed to density fluctuations in the matter, is best epitomized in the cosmic string scenarios, first noted by

TABLE III

GALAXY FORMATION SEEDS

1. **Quantum Induced Gaussion Adiabatic Fluctuations with Harrison-Zeldovich Spectrum** (c.f. Guth and Pi)

2. **Cosmic Strings** (Kibble, Zeldovich, Vilenkin)
   - A) Accreting (Turok and Albrecht, Bennett and Buchet)
   - B) Exploding Superconducting (Ostriker, Thompson and Witten)

3. **Late Time Phase Transitions** (Hill, Schramm and Fry)

Kibble and Zeldovich[53] and later developed by Vilenkin.[54] The last few years these scenarios have divided themselves into two sub-catagories. One is the gravitationally accreting string, developed most fully by Turok and Albrecht,[55] with recent interesting simulation being carried out by Bennett and Buchet.[56] The other variant of this has been the exploding seed scenario, where the strings are superconducting. This model has been put forth by Ostriker, Thompson and Witten.[57] In the exploding scenario, instead of the strings being gravitational accretion points, the strings radiate and push the baryons about, thus creating a segregation between the baryonic matter and the non-baryonic matter. The exploding scenario is in some way a natural outgrowth of the earlier model of Ostriker and Cowie,[58] but in the earlier model they had no energy sources strong enough to push matter about on cluster scales. The superconducting strings provided them with that energy source.

A new alternative using topological remnants has recently been developed by Hill, Schramm and Fry.[59] In this variant, instead of coupling them to a phase transition back in the primitive early moments of the universe, it ties the topological remnants to a phase transition that occurs late, after decoupling. In this scenario, the late phase transition produces domain walls, strings, etc., which can be the seeds of structure formation. Because the transition occurs after decoupling, it produces the minimum possible fluctuations in the microwave background for a given structure that is produced. Since there would be no fluctuations on the surface of last scattering, the only induced fluctuations in the microwave background in this model are due to the propagation of the microwave photons through the potential wells in the transparent media and due to the seeds themselves changing during the propagation. If the universe were static and not expanding, the differential red shift/blue shift would cancel and there would be no net effect. However, because the universe is expanding while the photons are propagating, the red shift and blue shift do not quite cancel. It can be seen that in late time transitions, larger structures, giving a larger differential between the red shift and blue shift, would yield the largest microwave fluctuations. The maximum size structure that could be created in such a model can, in principle, be up to the horizon at the time of the phase transition, and that horizon is larger than any presently observed structure, including the giant structures noted by Tully,[60] Geller and Huchra.[61] However, it should also be remembered that if the evolution of the late-time structures leads to larger and larger structures, then this model may have the problem that will produce too much power on large scales, which would be exactly the opposite problem of the quantum fluctuation scenario. However, producing larger structures and consequently $\frac{\Delta T}{T}$ depends on the details of how the walls, strings, etc. evolve with time. Simulations of the type that were carried out for cosmic strings need to be carried out for late time phase transitions. Preliminary simulation work has been begun by Kawano,[62] and Press, Ryden and Spergel[63]. In any model for the simulations of domain wall evolution, one needs to make assumptions about the number of minima which produce the numbers of different types to domains. Futhermore, one also needs to make assumptions about the intercommutability of the domain walls which is yet to be proven, and one needs to look at the possibility that the vacuum minima are not all degenerate, but that there may be some weakly broken symmetry yielding one vacuum slightly preferable over the others. This latter possibility will mean that eventually the walls could disappear. If they were there long enough to generate structures and then disappear, one would avoid having the problem of too much power on large scales. In this latter possibility one might still retain small "balls of wall," which would behave like non-topological solitons.[64] Non topological solitons produced by such a late time phase transition could be very good seeds for making galaxy and structure, with the seeds distributed in some pattern depending on the evolution of the phase transition.[65]

Recently, Hill, Schramm and Widrow[87] have argued that Sine-Gordon walls seem to work very well and avoid the pitfalls of one wall dominating, as was seen in the simulation of Press et al. These late-time phase transitions are the most recent of the ideas for seeds and thus the least explored. However, as we will see if present trends and observations are verified and continue, this may be an extremely promising model. For example, Stebbins and Turner[66] have shown that this model and variations of it might easily give large scale velocity fields.

Before leaving the discussion of this model it should also be noted that the physics that could produce such a late time phase transition is probably no more ad hoc than the physics that is invoked to enable inflation to work and still obtain sufficiently small primordial fluctuations. In both cases there is some tuning and in both cases one is invoking a phase transition based on "new" physics. The toy model proposed in the initial paper[59] was actually motivated not to try to solve this problem but rather the solar neutrino problem, where it was noted that, if MSW mixing is right, then neutrinos have masses of $\sim 10^{-2}eV$. If that mass is generated out of some vacuum energy, then you naturally have a phase transition at the order of $\sim 10^{-2}eV$. If that phase transition is related to a GUT scale having GUT scale coupling of $\sim 10^{16}GeV$, then the compton wave length of the resulting Psuedo-Goldstone particles is $\sim 1Mpc$, thus yielding cosmological scales derived from particle considerations. Numerous alternative particle models that also yield late-time transitions have been proposed. For example, Dimopoulos[67] has noted that if one uses a running coupling constant, analogous to QCD, one can have that running coupling constant grow strong at some temperature such as $10^{-2}eV$, thus yielding a phase transition. Another alternative has been proposed by Fuller and Schramm,[68] where they note that if majorons exist and are produced by a phase transition at $\lesssim leV$, the majoron induced neutrino interaction enables those regions that first undergo the phase transition to work like neutrino fly paper gobbling up any neutrinos in the vicinity, thus creating a non-linear density enhancement. It is certain that many other late-time phase transition models can exist that would have some sort of generic properties of the type needed. Thus, just like the case of inflation where a variety of particle models can all inflate, we have here a variety of particle models that can all yield late-time structures that could be interesting.

OBSERVATIONAL CONSTRAINTS

Table IV summarizes some of the constraints on different candidates. For example, dark baryonic halos DBH are not compatable with CDM, since CDM would also cluster on small scales and would thus be present in enough quanity to produce the halos. Any large amount of DBH would then be unnecessary and difficult to understand. While there are no direct observations of DBH, searchers using micro-lensing may resolve this. Recent observations by Thuan, Gott and Schrader[69] argue that dwarf galaxies are distributed in the same patterns as are the brighter galaxies. If this continues to be borne out, it certainly will be a difficulty for any CDM plus biasing model, since such a model argues that dwarfs are more uniform than big bright galaxies.

Observations of dark halos around dwarf galaxies are inconsistent with HDM as that halo material, but HDM could well exist and only clump on much larger scales, so such observations are not wide-reaching in their implications. In fact, DBH may be quite appropriate for dwarfs in HDM models.

Peculiar velocites are certainly expected in all models on small scales (the earth goes around the sun, the sun around the galaxy, galaxy around the local group). However, for this peculiar motion to persist up to scales of the order of 50 Mpc, as the preliminary observations of the 7 Samurai[70] indicate and as the recent work of Dressler and Faber[71] supports, is very problematic for the CDM Gaussian fluctuation scenario, since that scenario will build everything up from small scales. Similarly, observation of structures much bigger than 50 Mpc, such as those claimed by Tully[60] and Geller and Huchra[61] are very problematic for models, building things up from small scales unless they are just a few rare accidents.

An observation that has impact on any model that starts with quantum fluctuations and the current limits on the anisotropy of the microwave background has to deal with the number of condensed objects observed at red shift $\gtrsim 4$. Any model that starts with small fluctuations and requires linear growth has difficulty in producing large numbers of objects at red shifts much greater than unity. While quasars are known to exist at high red shifts,

TABLE IV
CONSTRAINTS

Dark Baryonic Halos (DBH) (Brown Dwarfs, Jupiters, Blackholes)
Not compatible with CDM. Halos of Dwarfs require either CDM or DBH.

CDM
requires significant BDM in failed galaxies.

HDM
requires either cosmic strings or late time phase transitions; it is not compatible with quantum Gaussian fluctuations.

CDM with Quantum Gaussian fluctuations
not compatible with
a. high cluster-cluster correlations
b. high large scale velocity flows
c. coherent structures $\gtrsim 50$ Mpc
d. dwarf galaxies being distributed like bright galaxies

Quantum Gaussian Adiabatic Fluctuations
not compatible with current limits on $\delta T/T$ and
large numbers of condensed objects at $Z \gtrsim 4$

Microwave Anisotropy Limits $\delta T/T \lesssim 5 \times 10^{-6}$
If found only compatible with late-time transitions.

Submillimeter Excess
would require energy input at $Z > 10$. Need objects to form early or decay of particles or topological defects, neither consistent with CDM plus quantum.

recent reports are that some galaxy-like objects may exist back then. The question is: how ubiquitous are these objects? If they are rare multi-sigma fluctuations, then all may still be well. However, if they are truly common, that is, if standard structures really started forming and yielded condensed objects at high Z, then we really are forced to some sort of topological model.

Furthermore, if the microwave limits are continued to be brought down and eventually are shown to yield fluctuation limits of only $5 \cdot 10^{-6}$, it would only be compatable with a late time phase transition. All other models, including cosmic string models to produce structures, require the microwave background to have large magnitude anisotropies. Another microwave constraint that is important is the sub-millimeter excess of the Berkeley-Nagoya group.[72] If true, this requires a large amount of energy input at red shifts $\gtrsim 10$. Such energy input would either need objects to form at that enormously high red shift or have decay with emission of energy from either particles or topological defects. None of these possibilities is consistant with the standard CDM and primordial Gaussian fluctuation scenario.

One important large scale structure constraint is the correlation of clusters. Bahcall and Soneira[78] have argued that clusters are more correlated than galaxies. Szalay and Schramm[79] have pointed out that such correlations, if real, support some sort of fractal initial seed patterns as opposed to Gaussian. In fact, string models may naturally yield such correlations.[55] However, projection effects[80] may be responsible at least in part for the previously reported correlations, but preliminary work from other groups also finds strong correlations.[61] More work with new data is clearly needed.

For future tests, beyond what we have already discussed, see Table V. Of course gravitational lensing is a key in our search for DBH. Gravitational lensing might also help find cosmic strings. Strings should produce pairs of images. A clump of pairs found by Cowie and Hu has recently been found to have even more pairs (S. Lilly, private communication). If verified, this may indicate a cosmic string still existing in that direction.

The x-ray background may also help us find the baryonic dark matter if it is not in our halos. X-ray observations can also help tell us something about galaxy structure and formation, since these early structures might inevitably produce x-rays. Thus, AXAF, when it flies, may help us to find the baryonic matter. COBE, which will fly in the near future, will be testing whether the sub-millimeter excess is real and will be pushing the limits on anisotropy. If they find something, this will of course tighten the arguments and point the direction for the models.

As to HDM, one of the best ways of finding it would be to find a mass for a neutrino. Tritium end-point measurements should soon eliminate ν_e as a candidate. Already limits

TABLE V

Future Tests

Gravitational Microlensing -
Tests DBH

AXAF -
Tests hot x-ray gas and activity at time of galaxy and structure formation.

COBE -
Tests submillimeter excess; pushes limits on $\delta T/T$

Other Limits on $\delta T/T$ -
Could push limits to $\sim 10^{-6}$; can also check for characteristic patterns for cosmic strings and domain walls

Limits on m_ν
Tritium endpoint should soon eliminate ν_e. Limits on ν_μ and ν_τ require either accelerator mixing experiments or another supernova with a neutral current detector operating.

Supernovae
In addition to supernovae limiting neutrino masses, they also limit axions and other exotic particles with $M \lesssim 10 MeV$.

Accelerator Tests
In addition to ν-mixing, also searches for supersymmetry. Searches for Higgs could reveal structure of vacuum. Identification of any new stable particle could yield the dark matter; width of Z^0 tests Big Bang Nucleosynthesis.

Antiprotons in cosmic rays
Limits constrain annihilations of CDM in galactic halo

Laboratory Searches for CDM
Axion searches using resonant cavities. Limits on ν's from annihilation in the Sun (and Earth) - using underground detectors. Direct searches (cryogenic detectors, etc.) should be able to detect WIMPs, if they exist.

from both laboratory experiments and the supernova seem to show that the mass of the ν_e is $\lesssim 20eV$. Experiments that are underway now will be able to push that limit down to $\sim 5eV$, thus eliminating it as a candidate for the dominant matter of the universe. However, the ν_e was never a serious candidate. Most likely the neutrino that would have the most mass will be the neutrino associated with the τ. Measuring the ν_μ and ν_τ masses requires either accelerator mixing experiments or another supernova with neutral current detectors operating to pick out the distribution in time of these species. Supernovae also could make a wonderful laboratory to further constrain other weakly interacting particles with masses $\lesssim 10MeV$, for example, supernova 1987a constrained axions.[73] The fact that the supernova emitted neutrinos on a time scale of $\sim$ 10s second argues that there is no significant axion emission. These limits force the axion to have masses $\lesssim 10^{-3}$ electron volts. That is, the only masses of the axion are the masses that would make it (if it exists at all) an important DM candidate.

Accelerator tests in the future are also very important. In addition to the neutrino mixing mentioned above, searches for super-symmetry could enable the dark matter particle to be found. Similarly, searches for the Higgs tell us something about the structure of the vacuum itself which leads to the formation of the seeds. In fact, identification of any new stable particle (even one not predicated) might reveal the dark matter. Of course the width of the Z from accelerators tests the neutrino counting agruments from Big Bang Nucleosynthesis and thus helps confirm our baryonic arguments.

Another observational test is the search for anti-protons in cosmic rays. These limits constrain the annihilation of CDM in the Galactic halo, since massive CDM particles would produce anti-particles via annihilation processes.

Perhaps the most exciting of all the dark matter constraining observations and experiments are the direct laboratory searches for CDM. This is a wonderful example of how new technology can be brought to play on an exciting problem. Axion searches using giant resident cavities may find this elusive particle directly. Limits on neutrino fluxes that might have been produced by the annihilation of CDM in the sun or even in the center of the earth might be found in underground detectors. Already the constraints from these kinds of experiments have eliminated and/or seriously constrained certain classes of models.[74,75] Perhaps the most exciting new detectors are the direct searches using cryogenic detectors and superconductivity. These should be able to detect any form of weakly interacting massive particle if it exists in the halo of our Galaxy. Details of the search possibilities are summarized in an excellent review by Primack, Sadoulet and Seckel.[76]

SUMMARY

The dark matter problem and its related problem of large scale structure generation is one of the most exciting and vital problems in physical science today. It is being approached from many angles by particle theorists, by astrophysical theorists, by astronomical observers at many wavelength regimes, and by particle experimentalists, both with accelerators and with non-accelerator experiments. While the ultimate answer to all our questions may not occur until we do experiments at the Planck scale (extrapolation of the Livingston Curve reveals that such experiments might[77] occur in the year 2150), it does seem that the important problem of finding out what the bulk of the matter of the universe is may be resolved by the end of this century.

ACKNOWLEDGMENTS

I would like to thank my Chicago colleagues for many interesting discussions, particularly Chris Hill, Michael Turner, and Rocky Kolb. I would also like to thank my frequent collaborators, Gary Steigman, Keith Olive and David Dearborn. This work is supported in part by NASA NAGW-1321, and the NSF AST 85-15447 at the University of Chicago and by the NASA/Fermilab Astrophysics Program, Grant # NAGW-1340.

REFERENCES

1. Guth, A. (1981) *Physics Review* **D23**, 374.
2. Linde, A. (1983) *Physics Letters* **129B**, 177.
3. Alpher, R., Bethe, H., and Gamow, G. (1948) *Physics Review* **73**, 803.
4. Alpher, R.A., Follin, J.W., and Herman R.C. (1953) *Physics Review* **92**, 1347.
5. Peebles, P.J.E. (1966) *Physical Review Letters* **16**, 410.
6. Wagoner, P., Fowler, W.A., and Hoyle, F. (1967) *Astrophysical Journal* **148**, 3.
7. Fowler, W., Greenstein, J., and Hoyle, F. (1961) *American Journal of Physics* **29**, 393 (see also ref. 32).
8. Ryter, C., Reeves, H., Gradstajn, E., and Audouze, J. (1970) *Astronomy and Astrophysics* **8**, 389.
9. Reeves, H., Audouze, J., Fowler W.A., and Schramm D.N. (1973) *Astrophyical Journal* **179**, 909.
10. Epstein, R., Lattimer, J., and Schramm, D.N. (1976) *Nature* **263**, 198.
11. Gott III, J.R., Gunn, J., Schramm, D.N., and Tinsley, B.M. (1974) *Astrophysical Journal* **194**, 543.
12. Rogerson, J., and York, D. (1973) *Astrophysical Journal* **186**, L95.
13. Geiss, J., and Reeves, H.(1972) *Astronomy and Astrophysics* **18**, 126.
14. Black, D. (1971) *Nature* **234**, 148.
15. Yang, J., Schramm, D., Steigman, G., and Rood, R. (1979) *Astrophysical Journal* **227**, 697.
16. Rood, R.T., Steigman, G. and Tinsley, B.M. (1976), *Astrophysical Journal* **207**, L57.
17. Yang, J., Turner, M.S., Steigman, G., Schramm, D.N., and Olive, K.A. (1984) *Astrophysical Journal* **281**, 493.
18. Olive, K., Turner, M., Steigman, G., Schramm, D.N. and Yang, J. (1980) *Astrophysical Journal* **246**, 557.
19. Spite, J. and Spite, F. (1981) *Astronomy and Astrophysics* **115**, 357.
20. Steigman, G., Schramm, D.N. and Gunn, J.E. (1977) *Physics Letters* **66B**, 202.
21. Schramm, D.N. and Steigman, G. (1984) *Physics Letters* **141B**, 337.
22. Cline, D., Schramm, D., and Steigman, G. (1987) *Comments on Nuclear and Particle Physics* **17**, 145.
23. Freese K. and Schramm, D.N. (1984) *Nuclear Physics* **B233**, 167.
24. Schramm, D. and Steigman, G. (1981) *General Relativity and Gravitation* **13**, 101.
25. Faber, S.M. and Gallagher, J. (1979) *Annual Review of Astronomy and Astrophysics* **17**, 135.
26. Kawano, L., Schramm, D., and Steigman, G. (1988) *Astrophysical Journal*, **327**, 750.

27. Strauss, M., Davis, M., Yahil, A. (1988) *University of California, Berkeley preprint.*

28. Loh, E. and Spillar, E. (1988) *Astrophysical Journal* **329**, 24.

29. Guth, A. (1981) *Physical Review D* **23**, 374.

30. Turner, M. (1988) in P. Galeotti and D.N. Schramm (eds.)*Proceedings of the NATO Advanced Study Institution: Gauge Theory in the Early Universe*, Kluwer Academic Publishers, Dordrecht.

31. Ryter, C., Reeves, H., Gradsztajn, E., and Auodouze, J. (1970) *Astronomy and Astrophysics* **8**, 389.

32. Fowler, W., Greenstein, J. and Hoyle (1962) *Journal of the Royal Astronomical Society* **6**, 148.

33. Dimopoulos, S., Esmailzadez, R., Hall, L., and Starkman, G. (1988) *Physical Review Letters* **60**, 7.

34. Brown, L. and Schramm, D. (1988) *Astrophysical Journal* **329**, L103.

35. Applegate, A., Hogan, C., and Scherrer, R. (1987) *Physics Review D* **35**, 115.

36. Alcock, C., Fuller, G., and Mathews, G. (1987) *Astrophysical Journal* **320**, 439.

37. Malaney, R., Fowler, W.A. (1988) *Astrophysical Journal* **333**, 14.

38. M. Tarazawo and K. Sato. (1989) *University of Tokyo preprint.*

39. Kurki-Suonio, R. and Matzner, R.A. (1988) *University of Texas preprint.*

40. Alcock, C., Fuller, G., Myer, B., and Mathews, G. (1988) *Livermore preprint.*

41. Kurki-Suonio, H., Matzner, R., Olive, K., and Schramm, D. (1989) *Astrophysical Journal*, in press.

42. Reeves, H. (1988) *Proceedings of Erice Symposium on Dark Matter.*
Audouze, J. (1988) *Proceedings of Recontre de Morionde.*

43. Dearborn, D., Schramm, D., Steigman, G., and Truran, J. (1989) *Astrophysical Journal* **34**, 788.

44. Helfand, D. (1989) *Columbia University preprint.*

45. Hegyi, D. and Olive, K. (1986) *Astrophysical Journal* **303**, 56.

46. Gunn, J. (1988) talk at ITP Santa Barbara.
York, D. (1988) talk at University of Chicago.

47. Bond, R. and Szalay, A. (1982) *Proceedings of Texas Relativistic Astrophysics Symposium*, Austin, Texas.

48. Turner, M.S., Wilczek, F., and Zee, A. (1983) *Physics Letters* **125B**, 519.

49. Crawford, D. and Schramm, D.N. (1982) *Nature* **298**, 538.

50. Zeldovich, Ya. and Novikov, I. (1967) *Relativisitic Astrophysics* (Soviet edition).

51. Lee, B., and Weinberg, S. (1977) *Physical Review Letters* **38**, 1237.

52. Frenk, C., White, S., Davis, M. and Efstatiou, G. (1985) *Astrophysical Journal* **292**,

371.

53. Kibble, T. (1980) *Physics Reports* **67**, 183.
    Zeldovich, Ya., (1981) *Nature.*
54. Vilenkin, A. (1985) *Physics Reports* **121**, 263.
55. Albrecht, A, Brandenberger, R., and Turok, N (1986) *New Science* **114**, 40.
56. Bennett, D. and Buchet, F. (1988) *Fermilab preprint.*
57. Ostriker, J.P., Thompson, C., and Witten, E. (1986) *Physics Letters B* **180**, 231.
58. Ostriker, J. and Cowie, C. (1981) *Astrophysical Journal* **243**, L127.
59. Hill, C., Schramm, D. and Fry, J. (1989) *Comments on Nuclear and Particle Physics* **19**, 25.
60. Tully, B. (1988) Presentation at Aspen Workshop on Large Scale Structure.
61. Geller, M. and Huchra, T. (1989) *Proceedings of Berkeley Part/Astro Workshop.*
62. Kawano, L. (1989) University of Chicago Thesis.
63. Press, W., Rydon, B., and Spergel, D. (1989) *Astrophysical Journal*, in press.
64. Lee, T.D. (1987) *Physics Review D* **35**, 3640.
    L. Widrow (1989) *Harvard University preprint.*
65. Griest, K. and Kolb, E. (1989) *FNAL preprint.*
66. Stebbins, A. and Turner, M. (1989) *FNAL preprint.*
67. Dimopoulos, S. and Starkman, G. (1989) private communication.
68. Fuller, G. and Schramm, D. (1989) in preparation.
69. Thuan, T., Gott, J.R., and Schrader, R. (1989) *University of Virginia preprint.*
70. Burstein, D. et al. (1986) in B. Madore and B. Tully (eds.), *Galaxy Distances and Deviations from Universal Expansion*, Reidel, Dordrecht, p.23.
71. Dressler, A. and Faber, S. (1989) *Proceedings of Texas Symposium on Relative Astrophysics.*
72. Lang, A., (1988) *Proceedings of Berkeley Part/Astro Workshop.*
73. Mayle, R., Wilson, J, Ellis, J., Olive, K., Schramm, D., Steigman, G. (1988) *Physics Letters B* **203**, 188.
    Borrows, A., Brinkmann, R., and Turner, M. (1989) *Physical Review Letters*, in press.
74. Olive. K. and Srednicki, M. (1988) *Physics Letters B* **205**, 553.
75. Gelmini, G. (1988) *Proceedings of Erice Symposium on Dark Matter.*
76. Primack, J., Sadoulet, B, and Seckel, D. (1988) *Annual Review of Nuclear Particle Science* **38**, 751.
77. Lederman, L. and Schramm, D.N. (1989) *From Quarks to the Cosmos*, W.H. Freeman, New York.
78. Bahcall, N. and Soniera, R. (1983) *Astrophysical Journal* **270**, 20.

79. Szalay, A. and Schramm, D. (1985) *Nature* **314**, 718.

80. Primack, J. and Deckel, A. (1989) *Santa Cruz preprint.*

81. Schramm, D. and Kawano, L. (1989) *Proceedings of the Grenoble symposium on slow neutrons.*

82. Mampe, W., Ageron, P., Bates, J., Pendebury, J., and Steyerl, A. (1989) *Proceedings of the Grenoble sympoisum on slow neutrons.*

83. Gallagher, J., Schramm, D., and Steigman, D. (1989) *Comments on Astrophysics* **XIV**, 97-106.

84. Dorfon, J. (1989) *SLC results presented at Madrid meeting of European Phusical Society.*

85. Hobbs, L, Pilachowski, C., and DeYoung, D. (1989) *Astrophysical Journal*, in press.

86. York, D., Dopita, M., Green, R., and Bechtold, J. (1986) *Astrophysical Journal* **311**, 610.

87. Hill, C., Schramm, D., and Widrow, L. (1989) *Science*, submitted